

# Switching of the vortex polarity in a magnetic nanodisk by a DC current

Denis D. Sheka,<sup>1,\*</sup> Yuri Gaididei,<sup>2</sup> and Franz G. Mertens<sup>3</sup>

<sup>1</sup>*National Taras Shevchenko University of Kiev, 03127 Kiev, Ukraine*

<sup>2</sup>*Institute for Theoretical Physics, 03143 Kiev, Ukraine*

<sup>3</sup>*Physics Institute, University of Bayreuth, 95440 Bayreuth, Germany*

(Dated: June 21, 2007)

We study the dynamics of a vortex state nanodisk due to a dc spin current, perpendicular to the disk plane. The irreversible switching of the vortex polarity takes place above some threshold current. The detailed description of these processes is obtained by spin-lattice simulations.

PACS numbers: 75.10.Hk, 75.40.Mg, 05.45.-a, 72.25.Ba, 85.75.-d

The spin torque effect, which is the change of magnetization due to the interaction with an electrical current, was predicted by Slonczewski [1] and Berger [2] in 1996. During the last decade this effect was tested in different magnetic systems [3, 4, 5] and nowadays it plays an important role in spintronics [6, 7]. Recently the spin torque effect was observed in vortex state nanoparticles. In particular, circular vortex motion can be excited by an AC [8] or a DC [9] spin-polarized current. Very recently it was predicted theoretically [10] and observed experimentally [11] that the vortex polarity can be controlled using a spin-polarized current. This opens up the possibility of realizing electrically controlled magnetic devices, changing the direction of modern spintronics [12].

It was shown in [10] that in easy-plane Heisenberg magnets a spin-current which flows perpendicular to the nanoparticle plane acts as an effective DC magnetic field making energetically unfavorable one of vortex polarity states. In this Letter we study the magnetic vortex dynamics in nanodots excited by the spin-polarized current, using the pillar structure, described in detail in Refs. [10, 13]. We show that the dipolar interaction crucially changes the physical picture of the vortex dynamics, breaking the axial symmetry of the system, i.e. the z-component of the momentum can be not conserved. Qualitatively speaking the dipolar interaction makes two main effects [14]: (i) there appears an effective uniaxial anisotropy of the easy-plane type, which is caused by the faces surface magnetostatic charges and (ii) there appears a nonhomogeneous effective in-plane anisotropy, which is caused by the edge surface charges (surface anisotropy). Due to the surface anisotropy the magnetization near the disk edge is constrained to be tangential to the boundary, which prevents its precession near the edge. That is why a simple picture of rotational vortex, which perfectly works for the Heisenberg magnet [10] should be revised for the nanodot with account of the dipolar interaction.

Heisenberg exchange and dipolar interactions [15]:

$$\mathcal{H} = -\frac{\ell}{2} \sum_{\langle \mathbf{n}, \delta \rangle} \mathbf{S}_{\mathbf{n}} \cdot \mathbf{S}_{\mathbf{n}+\delta} + \frac{1}{8\pi} \sum_{\substack{\mathbf{n}, \mathbf{m} \\ \mathbf{n} \neq \mathbf{m}}} \frac{\mathbf{S}_{\mathbf{n}} \cdot \mathbf{S}_{\mathbf{m}} - 3(\mathbf{S}_{\mathbf{n}} \cdot \mathbf{e}_{\mathbf{nm}})(\mathbf{S}_{\mathbf{m}} \cdot \mathbf{e}_{\mathbf{nm}})}{|\mathbf{n} - \mathbf{m}|^3}. \quad (1)$$

Here  $\mathbf{S}_{\mathbf{n}}$  is a unit vector which determines the spin direction at the lattice point  $\mathbf{n}$ ,  $\ell = \sqrt{A/(\mu_0 M_S^2)}$  is the exchange length ( $A$  is the exchange constant,  $\mu_0$  is the vacuum permeability,  $M_S$  is the saturation magnetization), the vector  $\delta$  connects nearest neighbors, and  $\mathbf{e}_{\mathbf{nm}} \equiv (\mathbf{n} - \mathbf{m})/|\mathbf{n} - \mathbf{m}|$  is a unit vector. The lattice constant is chosen as a unity length.

It is known that as a result of competition between the exchange interaction and the dipolar one the ground state of a thin magnetically soft nanodisk is a vortex state: the magnetization lies in the disk plane XY in the main part of the disk being parallel to the disk edge, forming the magnetic flux-closure pattern characterized by the vorticity  $q = +1$ . At the disk center the magnetization distribution forms a vortex core, which is oriented either parallel or antiparallel to the z-axis. The former is characterized by a polarity  $p = +1$  and the latter  $p = -1$ . When electrical current is injected in the pillar structure, perpendicular to the nanodisk plane, it influences locally the spin  $\mathbf{S}_{\mathbf{n}}$  of the lattice through the spin torque [1, 2]

$$\mathbf{T}_{\mathbf{n}} = j \sigma \mathcal{A} \frac{\mathbf{S}_{\mathbf{n}} \times [\mathbf{S}_{\mathbf{n}} \times \hat{\mathbf{z}}]}{1 + \sigma \mathcal{B} \mathbf{S}_{\mathbf{n}} \cdot \hat{\mathbf{z}}}. \quad (2)$$

Here  $j = J_e/J_p$  is a normalized spin current,  $J_e$  is the electrical current density,  $J_p = \mu_0 M_S^2 |e| d / \hbar$ ,  $d$  is the disk thickness,  $e$  is the electron charge,  $\mathcal{A} = 4\eta^{3/2} / [3(1+\eta)^3 - 16\eta^{3/2}]$ ,  $\mathcal{B} = (1 + \eta)^3 / [3(1+\eta)^3 - 16\eta^{3/2}]$ , and  $\eta \in (0; 1)$  denotes the degree of the spin polarization;  $\sigma = \pm 1$  gives two directions of spin-current polarization.

The spin dynamics of the system is described by the modified Landau-Lifshitz-Gilbert equation

$$\dot{\mathbf{S}}_{\mathbf{n}} = -\mathbf{S}_{\mathbf{n}} \times \frac{\partial \mathcal{H}}{\partial \mathbf{S}_{\mathbf{n}}} - \alpha \mathbf{S}_{\mathbf{n}} \times \dot{\mathbf{S}}_{\mathbf{n}} + \mathbf{T}_{\mathbf{n}}. \quad (3)$$

The magnetic energy of nanodots consists of two parts:

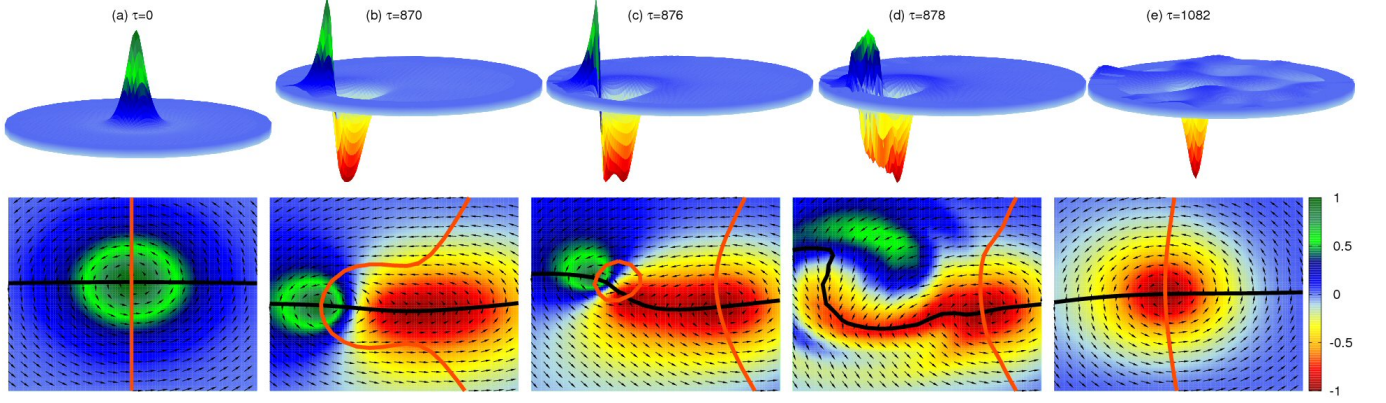


FIG. 1: (Color online) The time evolution of the vortex switching process from simulations: the top row shows the 3D distribution of the magnetization  $z$ -component, the bottom row corresponds to the in-plane magnetization distribution near the vortex core. Isosurfaces  $S_x = 0$  (black curve) and  $S_y = 0$  (orange curve) are plotted to determine the vortex position. The current  $j = -0.1$ .

Here the overdot indicates the derivative with respect to the dimensionless time  $\tau = \omega_0 t$  with  $\omega_0 = 4\pi\gamma M_S$ ,  $\alpha \ll 1$  is a damping coefficient, and  $\mathcal{H}$  is the Hamiltonian (1).

To study the vortex dynamics, we have performed numerical simulations of the discrete spin-lattice Eq. (3). We consider the case of thin nanodots where the magnetization does not depend on the  $z$ -coordinate. We have integrated numerically the set of Eqs. (3) over the square lattice using the fourth-order Runge-Kutta scheme with the time step  $\Delta\tau = 0.01$  and free boundary conditions. The lattice is bounded by a circle of diameter  $2L$ . In most of the simulations  $2L = 100$ ,  $h = 10$ ,  $\ell = 2.65$ ,  $\alpha = 0.01$ ,  $\sigma = +1$  and  $\eta = 0.26$ .

As an initial condition we use the vortex centered in the disk origin, see Fig. 1(a). To identify precisely the vortex position we use, similar to Ref. [16], the crossection of isosurfaces  $S_x = 0$  and  $S_y = 0$ , see the bottom row of Fig. 1. The vortex dynamics results from the force balance between a driving force (by the current), a dipolar force, a gyroscopical force, and a dissipative force. In the simulations we observe that when the vortex and the spin-current have the same polarization ( $j\sigma p > 0$ ) the vortex does not quit the center of the disk. However, for  $j\sigma p < 0$  ( $p = +1$ ,  $\sigma = +1$  and  $j < 0$  in our case) the vortex under the action of the current starts to move out of the disk center following a spiral trajectory, see Fig. 2(a). The spiral type of motion is caused by the gyroscopical force, which acts on a moving vortex perpendicular to its velocity in the same way as a Lorentz force acts on a charged particle in a magnetic field. The role of the charge plays a  $\pi_2$  topological charge  $Q = qp/2$ . The sign of  $Q$  determines the direction of the vortex motion, which is clockwise for  $p = +1$ . At some point (marked on Figs. 2 by the green symbol) the vortex switches its polarity ( $p = -1$ ). As is seen from Fig. 1, the mechanism of the vortex switching is very similar to the one observed in other systems [11, 17, 18, 19, 20, 21]. The

moving vortex excites a non-symmetric magnon mode with a dip situated towards the disk center. When the vortex moves away from the center, the amplitude of the dip increases, see Fig. 1(b). When the depth of the dip reaches a minimum ( $S_z = -1$ ), a pair of a new vortex and antivortex is created, see Fig. 1(c). The reason why the new-born vortex tears off his partner has a topological origin. The gyroscopical force depends on the total topological charge  $Q$ . Therefore it produces a *clockwise* motion for the original vortex ( $q = 1, p = 1, Q = 1/2$ ) and the new-born antivortex ( $q = -1, p = -1, Q = 1/2$ ) while the new-born vortex ( $q = 1, p = -1, Q = -1/2$ ) moves in the *anti-clockwise* direction. As a result the new vortex separates from the vortex-antivortex pair and rapidly moves to the origin, see Figs. 1(e) and 2(b). The attractive force between the original vortex ( $q = 1$ ) and the antivortex ( $q = -1$ ) facilitates a binding and subsequent annihilation of the vortex-antivortex pair, see Fig. 1(d).

The switching process has a threshold behavior. It occurs when the current  $|j| > j_{\text{sw}}$ , which is about 0.012 in our simulations, see Fig. 3. For stronger currents the switching time rapidly decreases. Using typical parameters for permalloy disks [10, 21] ( $\eta = 0.26$ ,  $A = 26$  pJ/m,  $M_S = 860$  kA/m,  $\alpha = 0.01$ ), we estimate that the time unit  $1/\omega_0 = 50$  ps, the critical current density is about  $0.1 \text{ A}/\mu\text{m}^2$  for a nanodot of 20nm thickness. The total current for a disk with diameter 200 nm is about 10 mA.

To summarize, we have studied the magnetic vortex switching under the action of a DC electrical current. We showed that the switching mechanism is essentially the same as in the cases when it is induced by a magnetic field pulse [17, 18, 19], by an AC oscillating [20] or rotating field [21], or by an in-plane electrical current [11]. There are two key points in this process: (i) the dipolar interaction causes the deformation of the magnetization profile for the fast moving vortex, which finally results in the creation of an additional vortex-antivortex pair,

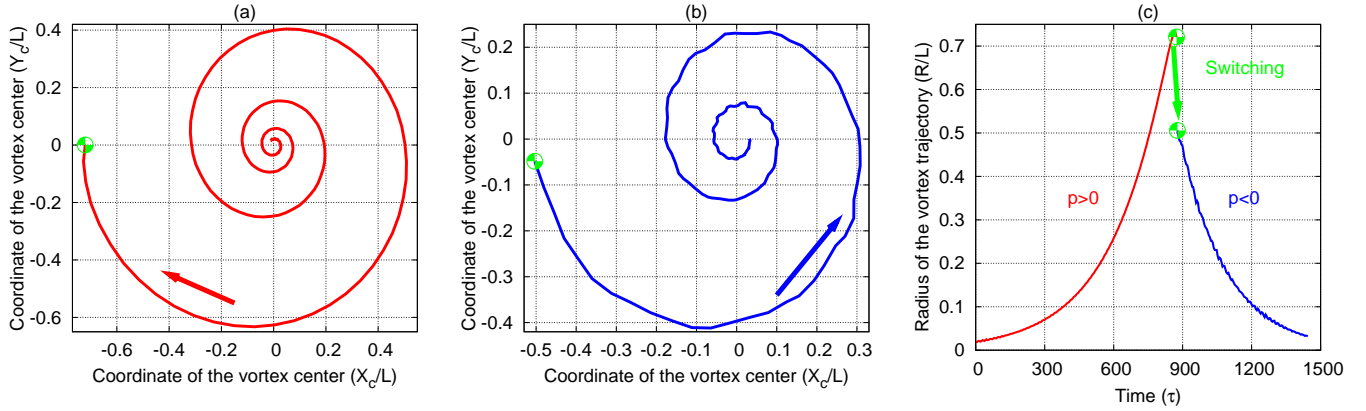


FIG. 2: (Color online). The vortex dynamics for  $j = -0.1$ . The vortex trajectory before the switching (a) and after it (b). The radius of the vortex trajectory as a function of time (c): at  $\tau = 877$  the vortex polarity is switched.

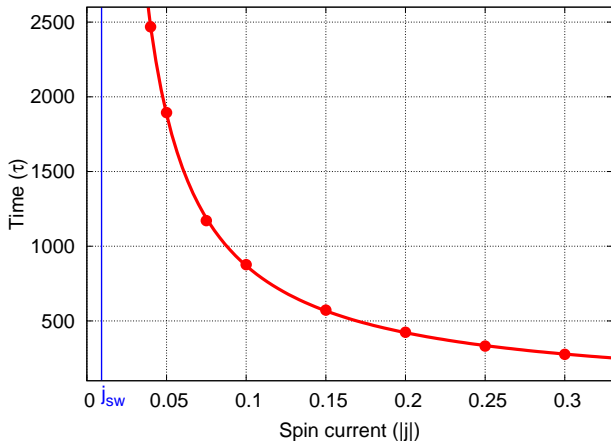


FIG. 3: (Color online). Switching time as a function of the applied current.

(ii) the topological charge structure of these three excitations secures the survival of the vortex with the new polarity direction or, in other words, the polarity switching. The detailed study of the vortex dynamics including the switching process is under construction.

The authors thank S. Komineas and V. Kravchuk for helpful discussions. D.S., Yu.G. thank the University of Bayreuth, where this work was performed, for kind hospitality and acknowledge the support from DLR grant No. UKR 05/055. D.S. acknowledges the support from the Alexander von Humboldt-Foundation.

\* Corresponding author. Electronic address: denis\_sheka@univ.kiev.ua

[1] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996), URL [http://dx.doi.org/10.1016/0304-8853\(96\)00062-5](http://dx.doi.org/10.1016/0304-8853(96)00062-5).

- [2] L. Berger, Phys. Rev. B **54**, 9353 (1996), URL <http://link.aps.org/abstract/PRB/v54/p9353>.
- [3] M. Tsoi, A. G. M. Jansen, J. Bass, W.-C. Chiang, M. Seck, V. Tsoi, and P. Wyder, Phys. Rev. Lett. **80**, 4281 (1998), URL <http://dx.doi.org/10.1103/PhysRevLett.80.4281>.
- [4] E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, and R. A. Buhrman, Science **285**, 867 (1999), URL <http://dx.doi.org/10.1126/science.285.5429.867>.
- [5] I. N. Krivorotov, N. C. Emley, J. C. Sankey, S. I. Kiselev, D. C. Ralph, and R. A. Buhrman, Science **307**, 228 (2005), URL <http://dx.doi.org/10.1126/science.1105722>.
- [6] Y. Tserkovnyak, A. Brataas, G. E. W. Bauer, and B. I. Halperin, Rev. Mod. Phys. **77**, 1375 (pages 47) (2005), URL <http://link.aps.org/abstract/RMP/v77/p1375>.
- [7] C. H. Marrows, Advances in Physics **54**, 585 (2005), ISSN 0001-8732, URL <http://www.informaworld.com/10.1080/00018730500442209>.
- [8] S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, and T. Ono, Phys. Rev. Lett. **97**, 107204 (pages 4) (2006), URL <http://link.aps.org/abstract/PRL/v97/e107204>.
- [9] V. S. Pribiag, I. N. Krivorotov, G. D. Fuchs, P. M. Braganca, O. Ozatay, J. C. Sankey, D. C. Ralph, and R. A. Buhrman, Nat Phys **advanced online publication**, (2007), ISSN 1745-2481, URL <http://dx.doi.org/10.1038/nphys619>.
- [10] J.-G. Caputo, Y. Gaididei, F. G. Mertens, and D. D. Sheka, Phys. Rev. Lett. **98**, 056604 (pages 4) (2007), URL <http://link.aps.org/abstract/PRL/v98/e056604>.
- [11] K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville, and T. Ono, Nat Mater **6**, 270 (2007), ISSN 1476-1122, URL <http://dx.doi.org/10.1038/nmat1867>.
- [12] R. P. Cowburn, Nat Mater **6**, 255 (2007), ISSN 1476-1122, URL <http://dx.doi.org/10.1038/nmat1877>.
- [13] A. D. Kent, B. Ozyilmaz, and E. del Barco, Appl. Phys. Lett. **84**, 3897 (2004), URL <http://link.aip.org/link/APL/84/3897/1>.
- [14] J.-G. Caputo, Y. Gaididei, V. P. Kravchuk, F. G. Mertens, and D. D. Sheka, *Effective anisotropy of thin*

- nanomagnets: beyond the surface anisotropy approach* (2007), arXiv:0705.1555, URL <http://arxiv.org/abs/0705.1555>.
- [15] A. I. Akhiezer, V. G. Bar'yakhtar, and S. V. Peletminskiĭ, *Spin waves* (North-Holland, Amsterdam, 1968).
  - [16] R. Hertel and C. M. Schneider, Phys. Rev. Lett. **97**, 177202 (pages 4) (2006), URL <http://link.aps.org/abstract/PRL/v97/e177202>.
  - [17] V. B. Waeyenberge, A. Puzic, H. Stoll, K. W. Chou, T. Tylliszczak, R. Hertel, M. Fahnle, H. Bruckl, K. Rott, G. Reiss, et al., Nature **444**, 461 (2006), ISSN 0028-0836, URL <http://dx.doi.org/10.1038/nature05240>.
  - [18] Q. F. Xiao, J. Rudge, B. C. Choi, Y. K. Hong, and G. Donohoe, Applied Physics Letters **89**, 262507 (pages 3) (2006), URL <http://link.aip.org/link/APL/89/262507/1>.
  - [19] R. Hertel, S. Gliga, M. Fahnle, and C. M. Schneider, Phys. Rev. Lett. **98**, 117201 (pages 4) (2007), URL <http://link.aps.org/abstract/PRL/v98/e117201>.
  - [20] K.-S. Lee, K. Y. Guslienko, J.-Y. Lee, and S.-K. Kim, *Ultrafast vortex-core reversal dynamics in ferromagnetic nanodots* (2007), cond-mat/0703538, URL <http://www.arxiv.org/abs/cond-mat/0703538>.
  - [21] V. P. Kravchuk, D. D. Sheka, Y. Gaididei, and F. G. Mertens, *Controlled vortex core switching in a magnetic nanodisk by a rotating field* (2007), arXiv:0705.2046, URL <http://arxiv.org/abs/0705.2046>.